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## From soilscares to landscapes: A landscape-oriented approach to simulate soil organic carbon dynamics in intensively managed landscapes

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## RESEARCH ARTICLE

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## Key Points:

- Conservation tillage and enhanced crop yields produce gains in soil organic carbon
- Enrichment ratio and bulk density vary spatially and temporally in intensively managed fields
- Management practices and hillslope location affect soil organic carbon dynamics

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## From soils to landscapes: A landscape-oriented approach to simulate soil organic carbon dynamics in intensively managed landscapes

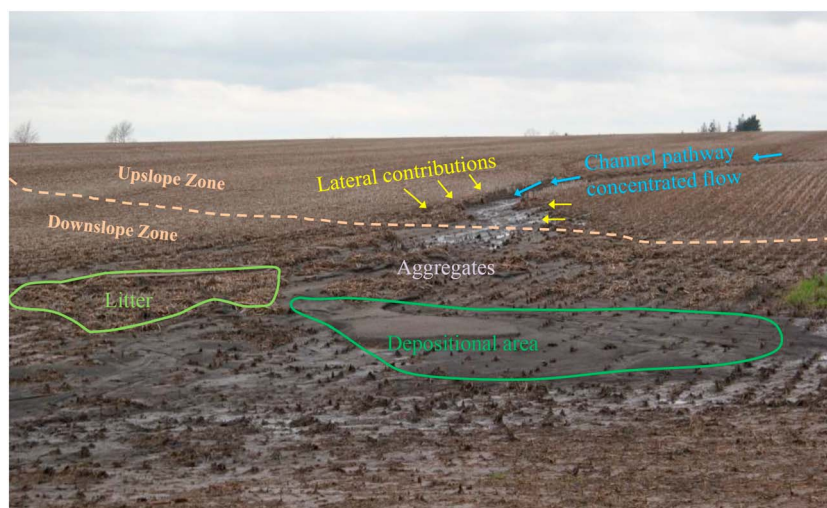
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**Abstract** Most available biogeochemical models focus within a soil profile and cannot adequately resolve contributions of the lighter size fractions of organic rich soils for enrichment ratio (ER) estimates, thereby causing unintended errors in soil organic carbon (SOC) storage predictions. These models set ER as constant, usually equal to unity. The goal of this study is to provide spatiotemporal predictions of SOC stocks at the hillslope scale that account for the selective entrainment and deposition of lighter size fractions. It is hypothesized herein that ER values may vary depending on hillslope location, Land Use/Land Cover (LULC) conditions, and magnitude of the hydrologic event. An ER module interlinked with two established models, CENTURY and Watershed Erosion Prediction Project, is developed that considers the effects of changing runoff coefficients, bare soil coverage, tillage depth, fertilization, and soil roughness on SOC redistribution and storage. In this study, a representative hillslope is partitioned into two control volumes (CVs): a net erosional upslope zone and a net depositional downslope zone. We first estimate ER values for both CVs I and II for different hydrologic and LULC conditions. Second, using the improved ER estimates for the two CVs, we evaluate the effects that management practices have on SOC redistribution during different crop rotations. Overall, LULC promoting less runoff generally yielded higher ER values, which ranged between 0.97 and 3.25. Eroded soils in the upland CV were up to 4% more enriched in SOC than eroded soils in the downslope CV due to larger interrill contributions, which were found to be of equal importance to rill contributions. The chronosequence in SOC storage for the erosional zone revealed that conservation tillage and enhanced crop yields begun in the 1980s reversed the downward trend in SOC losses, causing nearly 26% of the lost SOC to be regained.

## 1. Introduction

Soil organic carbon (SOC) is an important constituent of the Earth's fabric derived from the breakdown of above-ground plant residue, plant rhizomes, and root exudates. In intensively managed landscapes (IMLs), determining the SOC storage potential is of high importance for sustaining soil quality and crop productivity [e.g., Andrews et al., 2002; Sperow et al., 2003; Cambardella et al., 2004; Lal, 2011], as well as for mitigating rising Carbon Dioxide (CO<sub>2</sub>) levels in the atmosphere [e.g., Houghton, 2008; Kuhn et al., 2009; Hatfield and Parkin, 2012].

Several studies conducted over the last quarter of the century have emphasized the understanding of key biogeochemical processes affecting "above" and "below" ground carbon allocation, as well as other aspects of carbon dynamics and storage [e.g., Smith and Paul, 1990; Paustian et al., 1992, 2006; Gregorich et al., 1998; Richter et al., 1999; Metting et al., 1999; Lal, 2004; Polyakov and Lal, 2004; Jacinthe et al., 2009; Kuhn et al., 2009; Du and Walling, 2011; Li et al., 2012; Navas et al., 2012; Zhang et al., 2013]. Despite considerable gains in knowledge about SOC processes, most of these studies have been geospatially limited to the soil profile, thereby failing to account for the effects of landscape heterogeneity on SOC redistribution and storage [e.g., Tornquist et al., 2009]. In addition, the majority of the studies has been performed in punctually disturbed ecosystems, such as grasslands and forests, rather than constantly disturbed IMLs [e.g., Li et al., 1997; Yoo et al., 2005; Parton et al., 2007].

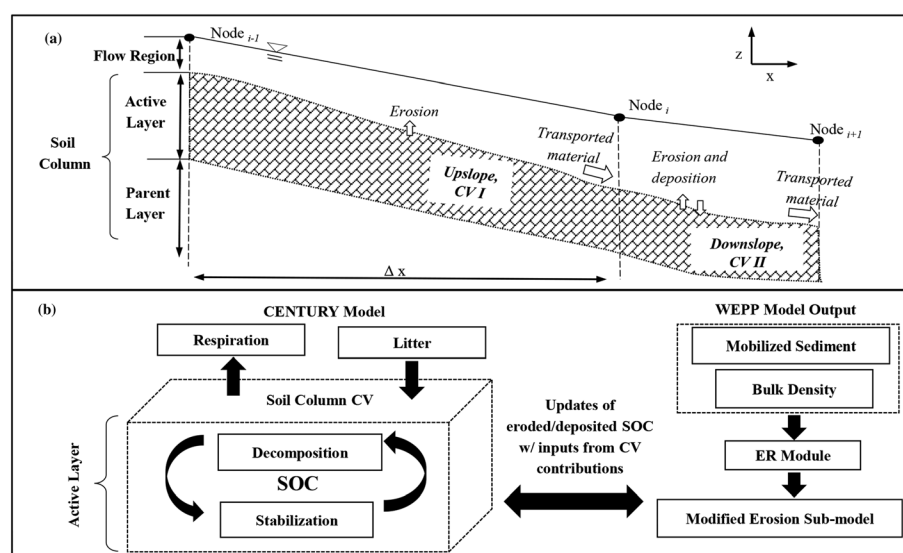


**Figure 1.** Soil and SOC redistribution. In an agricultural farm field, the collective effects of rain splash/runoff- and tillage-induced erosion/deposition redistribute finer soil particles and SOC heterogeneously along the hillslope.

Only a handful of models have the capacity to incorporate the effects of rainsplash/runoff and tillage erosion, defined herein as “collective erosion,” and deposition on SOC predictions at watershed scales [Van Oost *et al.*, 2000, 2005]. Rainsplash triggers redistribution of the finer fractions of soil through sheet erosion with lateral inputs to rills (Figure 1). Rills, in turn, erode on their own due to concentrated flows and convey the total eroded material downslope from erosion-dominated areas to deposition-dominated areas (Figure 1). Tillage has several effects on SOC redistribution and storage potential through a series of mechanistic processes [Moore and Burch, 1986; Van Oost *et al.*, 2000; Billings *et al.*, 2010; Lal, 2011]. These include the incorporation of residue within the soil profile (Figure 1) and fracturing of soil aggregates which exposes lighter size fractions of carbon-enriched material to selective entrainment by flow [Kuhn *et al.*, 2009; Papanicolaou *et al.*, 2009; Van Oost *et al.*, 2009]. Selective entrainment of the lighter size fractions affects the enrichment ratio (ER), which is a unique measure of change in available SOC through the enrichment or depletion of the finer size fraction of organic rich soils [Palis *et al.*, 1990; Wang *et al.*, 2013].

Changes in Land Use/Land Cover (LULC) and associated management practices in agricultural IMLs can lead to a higher degree of spatial heterogeneity and temporal variability in SOC redistribution during crop rotations uncommon in other systems [Parkin, 1993; Abaci and Papanicolaou, 2009; Dlugosz *et al.*, 2010; Kravchenko and Robertson, 2011; Du and Walling, 2011; Stavi and Lal, 2011; Navas *et al.*, 2012]. These different practices lead to changes in the percentage of bare soil, tillage depth, fertilization, and soil roughness. The degree that these changes influence SOC redistribution and storage may vary depending on the hillslope location and the magnitude of the hydrologic event. In fact, SOC changes may be significantly different in erosion-dominated (i.e., upslope) areas of a hillslope versus deposition-dominated (i.e., downslope) areas, with significant effects on net gains or losses in the SOC stored in these zones [Van Oost *et al.*, 2006; Wang *et al.*, 2015]. It is, therefore, not surprising that most of the available biogeochemical models, being soil profile models or “point models in space,” tend to overestimate or underestimate SOC storage predictions in IMLs as they do not account for outputs or inputs of mobilized SOC [e.g., Parton *et al.*, 1987; Paustian *et al.*, 1992; Harden *et al.*, 1999; Manies *et al.*, 2001; Mangan *et al.*, 2004; Jarecki *et al.*, 2008; Tornquist *et al.*, 2009; Wilson *et al.*, 2009; Van Oost *et al.*, 2006; Bortolon *et al.*, 2011; van Groenigen *et al.*, 2011; Vaccari *et al.*, 2012].

Some studies have linked existing biogeochemical models (e.g., Rothamsted Carbon (ROTH-C), DNDC (DeNitrification-DeComposition), and CENTURY) with lumped erosion models, such as those based on the Universal Soil Loss Equation or its modifications [e.g., Monreal *et al.*, 1997; Manies *et al.*, 2001; Zhang *et al.*, 2014], to account for losses of SOC along the downslope. These erosion models tend to provide long-term (100 year time window) estimates of eroded SOC fluxes, but are neither meant to capture the seasonal variability in SOC distribution [Harden *et al.*, 1999; Li *et al.*, 1997; Blaschke and Hay, 2001] nor account for SOC deposition [Gregorich *et al.*, 1998; Van Oost *et al.*, 2006].



**Figure 2.** Linked WEPP-CENTURY modeling framework. A hillslope is segmented into control volume (CV) sections composed of a flow region, soil active layer, and parent layer. (a) The WEPP model and ER module are used to simulate the mobilization, transport, and deposition of soil size fractions and SOC along the hillslope. (b) The integrative modeling framework allows the CV active layer to be updated via redistribution (from Figure 2a) as well as physical mechanisms (processes) of decomposition, stabilization, and incorporation.

Recently, significant modeling efforts have accounted for the dynamics of collective erosion and the role of deposition on SOC redistribution and storage [e.g., Billings *et al.*, 2010; Dlugosz *et al.*, 2010, 2012]. However, these models do not adequately incorporate the effects of selective entrainment and deposition of the finer size fraction of organic rich soils by the flow [Van Oost *et al.*, 2005; Dlugosz *et al.*, 2010, 2012]. The ER is currently assumed to be equal to unity [Teixeira and Misra, 1997] or to obtain a constant value greater than unity. On the contrary, it is anticipated that the range of ER values may vary depending on hillslope location and the magnitude of the hydrologic event leading to an overestimation of the SOC displaced [Kuhn *et al.*, 2009; Thompson *et al.*, 2010; Hu *et al.*, 2013].

The goal of this study is to provide spatiotemporal predictions of SOC stocks at the hillslope scale by accounting for the role of selective entrainment and deposition on SOC redistribution under different hydrologic and LULC conditions. SOC predictions are made following a similar discretization approach suggested by Berhe *et al.* [2012] where the hillslope is partitioned into two control volumes (CVs): an upslope zone and downslope zone illustrated in Figure 2a. An ER module is developed to account for selective entrainment and deposition in both zones. The backbone of the proposed modeling framework is based on the recognition that (1) interrill splash erosion is of equal importance to rill erosion for soil dislodgement and therefore should not be ignored in estimating ER for both the upslope (CV I) and downslope (CV II) zones [Hu *et al.*, 2013] and (2) ER estimations for CV II are strongly affected by material contributions from CV I which in turn affect the potential for material mobilization or settling in CV II under different hydrologic and LULC conditions.

The proposed landscape-oriented approach is demonstrated at the hillslope scale (0.01 km<sup>2</sup>) in a case study site of the U.S. Midwest, namely, Clear Creek, IA. The Clear Creek watershed is an ideal location for resolving SOC fluxes due to the data availability on soil, hydrologic, and land use properties [Papanicolaou and Abaci, 2008; Abaci and Papanicolaou, 2009].

We first estimate ER values for both CVs I and II at the hillslope scale for different hydrologic and LULC conditions. Second, using the improved ER estimates for the two CVs, we evaluate the effects that management practices with different crop cover, tillage depths, fertilization, and soil roughness characteristics have on SOC redistribution in CVs I and II. The simulations are supplemented with detailed site historic and current management practices as well as climate data (benchmark dates of the different management practices within the simulation period are detailed in section 3.2). To assess the predictive capabilities of the newly

developed framework, samples collected from representative field locations in Clear Creek for recent years are compared with model predictions.

## 2. Integrative WEPP-CENTURY Models

We consider the coupling of two established process-based models, namely, the Watershed Erosion Prediction Project, WEPP (version 2012.8) and the biogeochemical soil-column model, CENTURY (version 4.6). Detailed reviews of WEPP and CENTURY are not the focus here as they have already been presented in past publications [Flanagan *et al.*, 2007; Parton *et al.*, 1987; Tornquist *et al.*, 2009]. Instead, the emphasis is placed here on the steps involved in the coupling of the two models and the ER module.

The coupling of WEPP with CENTURY (Figure 2b) occurs here in a “loose” sense. The soil profile within a CV represents the spatial domain of the CENTURY model. It composes a top layer, known as the active layer (usually the top 20 cm in the soil profile [Papanicolaou *et al.*, 2010]), and a lower subhorizon layer, known as the parent layer. CENTURY simulates changes of SOC stocks within the soil active layer through inputs from residue incorporation and losses by decomposition [e.g., Parton *et al.*, 1987; Jarecki *et al.*, 2008; Tornquist *et al.*, 2009; Wilson *et al.*, 2009; Vaccari *et al.*, 2012; Zhang *et al.*, 2013]. However, CENTURY alone cannot explicitly simulate the SOC fluxes entering or exiting the soil profile via the action of collective erosion [Campbell *et al.*, 1996; Metting *et al.*, 1999].

The role of WEPP is to supplement these missing features in CENTURY. WEPP simulations can capture the downslope variability of key soil parameters (e.g., surface roughness, dry bulk density, critical erosional strength, and hydraulic conductivity) and provide textural updates of the active layer [Foster, 1982; Nearing and Nicks, 1998; Pieri *et al.*, 2007], all of which can strongly influence SOC fluxes.

However, WEPP in its present form cannot adequately resolve contributions of rill and interrill areas on ER estimates [Vázquez *et al.*, 2005; Thompson *et al.*, 2010] and is unable to simulate the ER of material being deposited within a CV as it tracks only the ER of material exiting from a CV [Flanagan and Nearing, 2000].

To address these limitations, an ER module is developed, which is interlinked with WEPP and CENTURY. The module considers separate transport capacity formulae for rill and interrill erosion [Yalin, 1963; Abrahams *et al.*, 2001] aiming to provide improved estimates of selective entrainment and deposition for both rill and interrill erosion processes. The separate capacity formulae for rill and interrill areas allow for a better representation of different soil size fraction redistribution and associated SOC enrichment for each of the two zones. For CV I, enrichment is calculated for net erosion as the ratio of the concentration of the eroded fraction contributed by rill and interrill processes to the total available concentration found in the active layer prior to an event (see equation (13)). Alternatively, enrichment for CV II is calculated for either net erosion or deposition depending on the “direction” of the net flux. Direction is strongly affected by the material contributions from CV I. Positive direction is defined here as net erosion, whereas negative directions as net deposition. In the case of net erosion, the ER in CV II is calculated similarly as in CV I. In the case of net deposition, the ER in CV II is calculated as the ratio of the concentration of the deposited material fraction in CV II to the concentration of the material fraction eroded from CV I derived by rill and interrill processes (see equation (14)).

The daily outputs of updated ER values along with the daily net soil fluxes and size fractions from the ER module and WEPP are aggregated to a monthly time scale and input into CENTURY to determine SOC stocks within a CV. Updates on SOC stocks due to the effects of decay and physicochemical stabilization of SOC are also estimated.

The following subsections describe the assumptions of the proposed landscape-oriented approach, as well as the enhanced erosion process formulation that the new framework offers.

### 2.1. Modeling Assumptions

The proposed landscape-oriented approach is based on the following assumptions:

1. The distribution of rainfall is uniformly applied to the CVs at the hillslope scale [Elhakeem and Papanicolaou, 2009]. Soil properties within each CV are treated as homogeneous but heterogeneous between the two CVs, which are updated during the simulations.
2. The impact of tillage events is to exacerbate the effects of rainfall-runoff erosion on SOC stocks rather than directly displacing soil in the downslope [Quine *et al.*, 1999; Van Oost *et al.*, 2005].



3. A fixed fraction of the SOC transported in runoff is considered to be mineralized so that the C loss due to mineralization of SOC in the transported soil can be estimated by a simple relation. In our study it is assumed that 20% of the mobilized material is mineralized [Lal, 2006; Yadav and Malanson, 2009].
4. Soil is mobilized and transported through both interrill and rill processes [Zhang et al., 2003; Wang et al., 2013], where rainsplash effects dominate the interrill areas [e.g., Gilley et al., 1985; Gabet and Dunne, 2003] and concentrated overland flow is the main driver for soil particle movement in rills [e.g., Römken et al., 2002; Rieke-Zapp and Nearing, 2005].
5. The capacity of a soil particle to bind SOC is proportional to its surface area and the affinity of its surface to hold carbon [Palis et al., 1997; Thevenot et al., 2010; Wäldchen et al., 2012; Wang et al., 2013].
6. The soil continuum is composed of both primary particles and aggregates [Foster et al., 1985]. The primary particles (i.e., clay, silt, and sand) are each assigned their median diameters. Aggregates are partitioned into small and large aggregates, with specific gravity values of 1.8 and 1.6, respectively. The size distribution and composition of mobilized soil particles is based on the availability of the range of size fractions found within the active layer of the soil column [Foster et al., 1985]. Rill and interrill areas are source contributors of different size fractions to the active layer. The eroding zone is treated as supply limited (i.e., no incoming material from upslope sections) [Yalin, 1963; Abrahams et al., 2001].
7. Surface residue is distributed homogeneously across the soil surface of each CV and is incorporated vertically within the soil active layer profile during a tillage event [Salinas-García et al., 2002; Flanagan et al., 2012].
8. SOC biogeochemical stabilization within the active layer is treated as a continuous process that includes not only supply contributions from decayed labile forms of SOC, such as root exudates and residue leachates, but also the decayed portions of incorporated residue and roots, which are relatively more decay resistant than fresh plant material [Six et al., 2002; Olchin et al., 2008].

## 2.2. Enhanced Model Formulation

In the sections below, we provide the basic relationship used to estimate SOC stocks within the active layer followed by the key formulation for estimating daily soil fluxes, enrichment ratios, textural updates of the active layer, and related monthly-aggregated SOC fluxes and changes.

Updates in soil flux inputs/outputs along with updates in textural and soil microclimate conditions affect rates of decomposition, stabilization, and respiration within the soil profile [Paustian et al., 2006]. Appendix A provides key formulation for the hydrologic component and Appendix A describes formulation for the decomposition, stabilization, and respiration processes. All formulation is presented below in index notation.

### 2.2.1. Estimation of SOC Stocks Within the Active Layer

The stock of SOC ( $\text{g C/m}^2$ ) present within the active layer of CV  $i$  at time  $j$ ,  $(\text{SOC}_{\text{ACT}})_i^j$ , is defined as follows:

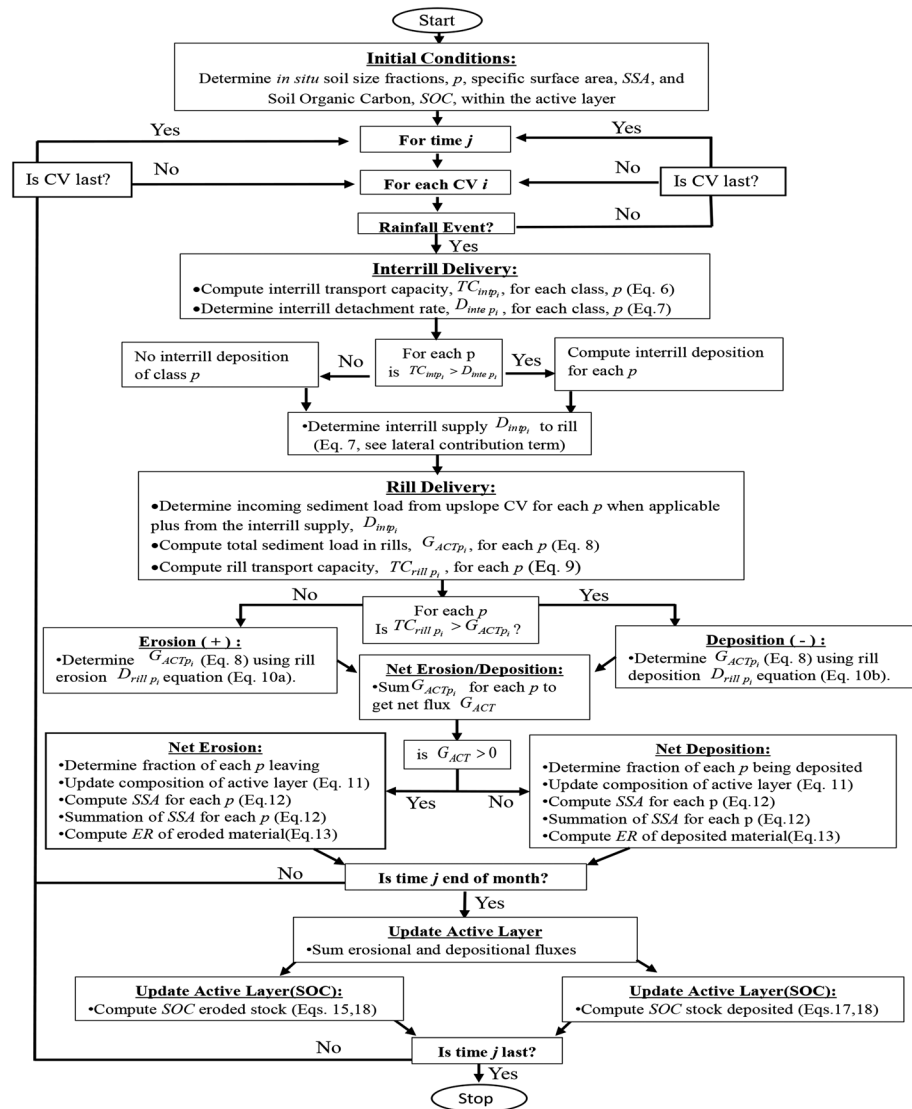
$$(\text{SOC}_{\text{ACT}})_i^j = \left( \rho_{\text{Bulk}_{\text{ACT}}} \left( \frac{M_{\text{Carbon}_{\text{ACT}}}}{M_{\text{Soil}_{\text{ACT}}}} \right) D_{\text{ACT}} \right)_i^j \quad (1)$$

where  $\rho_{\text{Bulk}_{\text{ACT}}}$  is the dry soil bulk density of the active layer at time  $j$  ( $\text{g/m}^3$ );  $M_{\text{Carbon}_{\text{ACT}}}$  is the mass of carbon in the active layer (g);  $M_{\text{Soil}_{\text{ACT}}}$  is the mass of soil within the active layer (g); and  $D_{\text{ACT}}$  is the active layer depth (m).

Studies in agricultural fields have shown that the dry bulk density values can fluctuate subseasonally or seasonally via management and microclimate perturbations [Logsdon and Karlen, 2004; Osunbitan et al., 2005; Burras et al., 2005]. To reflect these changes, we estimate the dry bulk density within the soil active layer,  $\rho_{\text{Bulk}_{\text{ACT}}}$ , of CV  $i$  at time  $j$ , with (assumption 2):

$$(\rho_{\text{Bulk}_{\text{ACT}}})_i^j = (\rho_{\text{till}})_i^j + (\Delta\rho_{\text{rf}} + \Delta\rho_{\text{wt}})_i^{j-DTE} \quad (2)$$

where  $\rho_{\text{till}}$  is the dry bulk density value following a particular tillage event ( $\text{g/m}^3$ );  $DTE$  is the number of days since the last tillage disturbance;  $\Delta\rho_{\text{rf}}$  is the increase in density due to rainfall consolidation ( $\text{g/m}^3$ ); and  $\Delta\rho_{\text{wt}}$  is the increase in density due to weathering consolidation ( $\text{g/m}^3$ ) that is mostly triggered by heavy equipment [e.g., Williams et al., 1984; Flanagan et al., 2007].



**Figure 3.** ER module and SOC stock updates. The enrichment ratios and SOC stock updates in the upslope and downslope zones are determined taking into account the mobilization and deposition of the different size fractions in both rill and interrill areas. The ER module considers the flow transport capacity in each area of the CV and updates the composition of the active layer with each event.

## 2.2.2. Estimation of Net Soil Fluxes and ER—"The ER Module"

The steps involved in estimating the net soil fluxes and ER for daily rainfall-runoff events via WEPP and the ER module are outlined in Figure 3 and are as follows: (1) determination of interrill contributions of different size fractions (five fractions are used in this study) using an improved interrill transport capacity formula, see equations (5), (6), (7a), and (7b); (2) determination of rill contributions and routing of the transported soil flux of different size fractions (both interrill and rill contributions) along the downslope, see equations (8), (9), (10a), and (10b); (3) updating the composition of the active layer based on the net fluxes of material of each size fraction, equation (11); and (4) aggregating the daily net fluxes to a monthly scale to estimate losses or gains in SOC stocks, see equations (12)–(17).

### 2.2.2.1. Size Fractions

We take advantage of existing WEPP features to represent size fractions of soil (denoted by  $p$ ). WEPP employs five size fractions ( $p = 1, \dots, 5$ ) representing the soil matrix as both primary particles and aggregates [Foster et al., 1985]. The primary particle diameters  $d_{\text{clay}}$ ,  $d_{\text{silt}}$ , and  $d_{\text{sand}}$  are assigned median values of 0.002, 0.010,



and 0.2 mm, respectively. The diameter,  $d_{smag}$ , of small aggregates (mm) is approximated using the following empirical equations where  $cl$  denotes the clay percentage [Foster *et al.*, 1985]:

$$d_{smag} = \begin{cases} 0.030 & cl < 0.25 \\ 0.2(cl - 0.25) + 0.030 & 0.25 \leq cl \leq 0.60 \\ 0.100 & cl > 0.60 \end{cases} \quad (3)$$

For large aggregates, the diameter,  $d_{lgag}$  (mm), is determined as follows:

$$d_{lgag} = \begin{cases} 0.300 & cl \leq 0.15 \\ 2cl & cl > 0.15 \end{cases} \quad (4)$$

In WEPP, small and large aggregates are assigned to specific gravity values of 1.8 and 1.6, respectively. If coarser material fractions were present, WEPP can easily incorporate them by modifying the number of soil size fractions  $p$ .

### 2.2.2.2. Interrill Erosion

For each size fraction  $p$ , the interrill detachment rate,  $D_{inte\ p_i}$  (g/s/m), is estimated as:

$$D_{inte\ p_i} = f_p D_{inte_i} \quad (5)$$

where  $f_p$  is the mass fraction of size fraction  $p$  in the active layer and  $D_{inte}$  (g/s/m) is calculated as  $D_{inte_i} = K_{int_i} l_e \sigma_{int_i} R_{int_i}$  [Foster *et al.*, 1995] where  $K_{int_i}$  is the interrill erodibility (g/s/m<sup>4</sup>);  $l_e$  is the effective rainfall intensity (m/s);  $\sigma_{int_i}$  is the interrill runoff rate (m/s); and  $R_{int_i}$  is the width of the interrill area.

To estimate soil contributions to rills from interrill areas, we introduce into the ER module the Abrahams *et al.* [2001] transport capacity formula, rewritten for each size fraction as follows:

$$TC_{intp_i} = \phi \rho_{sp} [g(SG_p - 1) d_p]^{0.5} d_p \quad (6)$$

where

$$\begin{aligned} \phi &= a \tau_{int\ p_i}^* 1.5 \left( 1 - \frac{\tau_{c\ int\ p_i}^*}{\tau_{int\ p_i}^*} \right)^{0.5} \left( \frac{u_{int_i}}{u_{*int_i}} \right)^c \left( \frac{w_{sp}}{u_{*int_i}} \right)^{-0.5} \\ a &= 10^{-0.42 Cr_{int_i} / Dr_{int_i}^{0.2}} \\ c &= 1 + 0.42 Cr_{int_i} / Dr_{int_i}^{0.2} \end{aligned}$$

where  $TC_{intp_i}$  (g/s/m) is the sediment transport capacity of size fraction  $p$  in the CV;  $SG_p$  is the particle specific gravity (–) of each size fraction  $p$ ;  $\rho_{sp}$  is the particle density (g/m<sup>3</sup>);  $d_p$  is the median particle diameter (m) for each fraction  $p$ ;  $\tau_{int\ p_i}^*$  is the dimensionless shear stress acting on size fraction  $p$  (–);  $\tau_{c\ int\ p_i}^*$  is the dimensionless critical shear stress (–);  $u_{int_i}$  is the interrill flow velocity (m/s);  $u_{*int_i}$  is the shear velocity (m/s);  $w_{sp}$  is the settling velocity (m/s) of the median particle diameter; and  $a$  and  $c$  are regression coefficients dependent on the concentration of roughness elements;  $Cr_{int_i}$  (–), and the characteristic roughness diameter,  $Dr_{int_i}$  (m) in the CV.

If the transport capacity of the size fraction,  $TC_{intp_i}$ , is greater than its detachment rate, (i.e.,  $TC_{intp_i} > D_{inte\ p_i}$ ), then the interrill supply,  $D_{intp_i}$ , of the size fraction to the rill (per unit rill area; kg/s/m<sup>2</sup>) is determined as follows:

$$D_{intp_i} = \frac{D_{inte\ p_i}}{w_{rill}} \quad (7a)$$

where  $w_{rill}$  is the width of the rill (m). On the other hand, if  $TC_{intp_i} < D_{inte\ p_i}$ , then  $D_{intp_i}$  (g/s/m<sup>2</sup>) is calculated as follows:

$$D_{int\ p_i} = \frac{1}{w_{rill}} \left[ D_{inte\ p_i} - \frac{\beta w_{sp}}{\sigma_{int_i}} (D_{inte\ p_i} - TC_{int\ p_i}) \right] \quad (7b)$$

where  $\beta$  is a turbulence resuspension coefficient (assigned a value of 0.5) and  $w_{sp}$  is the settling velocity for size fraction  $p$  (m/s) estimated using the approach described in Fox and Papanicolaou [2007].

### 2.2.2.3. Rill Erosion and Downslope Particle Transport

A steady state form of the 1-D sediment continuity equation is used to account for the collective net fluxes contributed in the downslope by the interrill and rill areas. The downslope flux equation for each size

fraction is solved along a rill where the contributions of interrill areas are assumed to occur laterally along the rill longitude:

$$G_{ACTp,i} = D_{int\ p_i} + D_{rill\ p_i} \quad (8)$$

where  $G_{ACTp}$  (g/m/s) is the transported soil load of size fraction  $p$  derived from the active layer within CV  $i$ ;  $(\cdot)$  implies the derivative of  $G_{ACTp}$  in the downslope;  $D_{int\ p_i}$  is the net interrill flux rate of size fraction  $p$  (g/s/m<sup>2</sup>) determined with equations (7a) and (7b); and  $D_{rill\ p_i}$  is the net rill flux rate of size fraction  $p$  (g/s/m<sup>2</sup>).

For determining whether net erosion or deposition is occurring within CV  $i$ , the rill flow transport capacity,  $TC_{rill\ p_i}$  (g/m/s), is determined using the Yalin [1977] formula:

$$\frac{TC_{rill\ p_i}}{SG_p d_p \rho^{0.5} \tau_{o\ rill\ p_i}^{0.5}} = 0.635 \delta \left[ 1 - \frac{1}{\beta_0} \ln(1 + \beta_0) \right] \quad (9)$$

where

$$\beta_0 = 2.45 (SG_p)^{-0.4} (\tau_{c\ rill\ p_i}^*)^{0.5} \delta$$

$$\delta = \frac{\tau_{rill\ p_i}^*}{\tau_{c\ rill\ p_i}^*} - 1$$

$$\tau_{rill\ p_i}^* = \frac{\tau_{o\ rill\ p_i}}{\rho (SG_p - 1) g d_p}$$

$$\tau_{c\ rill\ p_i}^* = \frac{\tau_{c\ rill\ p_i}}{\rho (SG_p - 1) g d_p}$$

where  $SG_p$  is the particle specific gravity (–) of size fraction  $p$ ;  $g$  is the acceleration due to gravity (m/s<sup>2</sup>);  $\rho$  is the density of water (g/m<sup>3</sup>);  $d_p$  is the particle diameter (m) of size fraction  $p$ ;  $\tau_{o\ rill\ p_i}$  is the hydraulic shear stress (Pa);  $\tau_{c\ rill\ p_i}^*$  is the critical erosional strength (Pa);  $\tau_{rill\ p_i}^*$  denotes the dimensionless shear stress acting on the rill bed;  $\tau_{c\ rill\ p_i}^*$  denotes the dimensionless critical shear stress (–), and  $\beta_0$  and  $\delta$  are dimensionless parameters that reflect the soil properties [Foster and Meyer, 1972; Alonso et al., 1981; Finkner et al., 1989].

When net erosion occurs for a size fraction (i.e.,  $TC_{rill\ p_i} > G_{ACTp_i}$ ) the rill erosion rate,  $D_{rill\ p_i}$  (kg/s/m<sup>2</sup>), is determined as follows:

$$D_{rill\ p_i} = K_{rill\ p_i} (\tau_{o\ rill\ p_i} - \tau_{c\ rill\ p_i}) \left( 1 - \frac{G_{ACTp_i}}{TC_{rill\ p_i}} \right) \quad (10a)$$

where  $K_{rill\ p_i}$  denotes the rill erodibility (s/m) that is a function of surface roughness and soil textural properties. When there is net deposition (i.e.,  $TC_{rill\ p_i} < G_{ACTp_i}$ ),  $D_{rill\ p_i}$  is determined as follows:

$$D_{rill\ p_i} = \frac{\chi W_{sp}}{q_{rill\ i}} (TC_{rill\ p_i} - G_{ACTp_i}) \quad (10b)$$

where  $q_{rill\ i}$  is the unit discharge (m<sup>2</sup>/s) in the rill;  $w_{sp}$  is the settling velocity; and  $\chi$  (~0.5) is a raindrop-induced turbulent coefficient [Lindley et al., 1995].

#### 2.2.2.4. Active Layer Composition Updates

Equations (5) to (10a) and (10b) are solved for each size fraction to accommodate textural changes in the soil active layer in CENTURY. At the end of each time step, the updated mass fraction,  $f_{ACTp_i}^{j+1}$  of each size fraction  $p$  in the soil active layer of CV  $i$  at time  $j+1$  is determined as follows [Papanicolaou et al., 2010]:

$$f_{ACTp_i}^{j+1} = \frac{Mass_{ACTp_i}^{j+1}}{\sum_p Mass_{ACTp_i}^{j+1}} \quad (11)$$

where

$$Mass_{ACTp_i}^{j+1} = Mass_{ACTp_i}^j - (Mass_{erod\ p_i}^j - Mass_{depo\ p_i}^j) \pm A_{CVi} DZ \rho_{si} f_{PARp_i}$$

where  $Mass_{ACTp_i}^j$  is the mass with size fraction  $p$  in the active layer at time  $j$  (g);  $Mass_{erod\ p_i}^j$  is the mass with size fraction  $p$  (g) that eroded within time interval  $DT$ ;  $Mass_{depo\ p_i}^j$  is the deposited mass with size fraction  $p$  (g)

within  $DT$ ;  $A_{CVi}$  is the surface cross-sectional area ( $m^2$ ) of CV  $i$ ;  $f_{PARpi}$  is the mass fraction of size fraction  $p$  transferred to (– under net deposition) or incorporated from the parent layer (+ under net erosion);  $\rho_{si}$  is the bulk density of the parent layer (under net erosion) or the active layer (under net deposition); and  $DZ_i$  is the net change in bed elevation (m) for CV  $i$  accounting for the net flux of material for all size fractions and the soil porosity.

#### 2.2.2.5. Soil Enrichment and ER Determination

We determine the ER of mobilized and deposited soil in the CVs by determining the specific surface area of the active soil material as follows:

$$SSA = \sum_p f_{mp} \left( \frac{f_{smdp} SSA_{sdp} + f_{sltp} SSA_{sltp} + f_{clyp} SSA_{clyp} + f_{orgp} SSA_{org}}{1 + f_{orgp}} + \frac{f_{orgp} SSA_{org}}{1.73} \right) \quad (12)$$

where  $f_{mp}$  is the proportion of size fraction  $p$  in the material being considered (i.e., active layer, mobilized or deposited material);  $f_{smdp}$ ,  $f_{sltp}$ ,  $f_{clyp}$ , and  $f_{orgp}$  are the mass proportions of sand, silt, clay and organic matter in each size fraction  $p$ , respectively; and  $SSA_{sdp}$ ,  $SSA_{sltp}$ ,  $SSA_{clyp}$ , and  $SSA_{org}$  are the specific surface areas of sand, silt, clay and organic carbon, respectively, taken as 0.05, 4.0, 20, and 1000  $m^2/g$ , respectively [Sposito, 1989; Flanagan and Nearing, 2000]. For in situ soils,  $f_{mp}$  is the proportion of size fraction  $p$  in the soil active layer, whereas for mobilized and deposited soils,  $f_{mp}$  is the proportion of size fraction  $p$  in the total eroded and deposited soil fluxes, respectively. The value 1.73 is used to convert the fraction of organic matter to organic carbon [e.g., Neitsch et al., 2002].

The capacity of a soil particle to bind SOC is proportional to the particles surface area [Palis et al., 1997; Wang et al., 2013], and the soil enrichment ratio of CV  $i$  at time  $j$ ,  $(ER_{ErodACT})_i^j$ , (assumption 5) can be expressed as follows:

$$(ER_{ErodACT})_i^j = \left( \frac{SSA_{ErodACT}}{SSA_{SOILACT}} \right)_i^j \quad (13)$$

where  $SSA_{ErodACT}$  is the specific surface area of eroded soil ( $m^2/g$ ); and  $SSA_{SOILACT}$  is the specific surface area of the in situ soil ( $m^2/g$ ). To determine the enrichment of the material being deposited within CV  $i$  at time  $j$ ,  $(ER_{DepoACT})_i^j$  the following expression is used:

$$(ER_{DepoACT})_i^j = \left( \frac{SSA_{DepoACT}}{SSA_{MobACT}} \right)_i^j \quad (14)$$

where  $SSA_{DepoACT}$  is the specific surface area of deposited soil ( $m^2/g$ ) and  $SSA_{MobACT}$  is the specific surface area of the total mobilized soil from which material is deposited ( $m^2/g$ ).

#### 2.2.2.6. Net SOC Fluxes Within the Soil Profile

The net flux of material,  $(G_{ACT})_i^j$  in  $g/s$ , from CV  $i$  at time  $j$  is calculated as the sum of the fluxes of all the size fractions (i.e.,  $(G_{ACT})_i^j = \sum_p (G_{ACTp} \times w_{fill})_i^j$ ). The calculated  $(G_{ACT})_i^j$  values are aggregated for each month to

estimate the loss or gain in SOC for the month. For net erosional events (i.e.,  $G_{ACT} > 0$ ), the loss of SOC for CV  $i$  in a given month  $j$ ,  $(SOC_{NetErodACT})_i^j$ , is estimated as follows:

$$(SOC_{NetErodACT})_i^j = (SOC_{ACT})_i^j \left( \frac{G_{ACT} ER_{ErodACT}}{\rho_{BulkACT} D_{ACT}} \right)_i^j DT \quad (15)$$

where  $\rho_{BulkACT}$  is obtained from equation (2); and  $ER_{ErodACT}$  is the enrichment ratio of monthly-aggregated material leaving the CV (see equation (13)).

Per assumption 3, the portion of  $(SOC_{NetErodACT})_i^j$  that is considered to be mineralized during transport,  $(SOC_{OXACT})_i^j$ , is estimated as follows:

$$(SOC_{OXACT})_i^j = f_{OXi} (SOC_{NetErodACT})_i^j \quad (16)$$

where  $f_{OXi}$  is a fixed fraction assumed to be 20% [Yadav and Malanson, 2009] in this study. For net depositional events ( $G_{ACT} < 0$ ), fluxes of SOC being deposited within CV  $i$  in month  $j$ ,  $(SOC_{NetDepoACT})_i^j$  are expressed as follows:

$$(SOC_{NetDepoACT})_i^j = (1 - f_{OXi-1}) (SOC_{NetErodACT})_{i-1}^j \frac{(G_{ACT})_i^j}{(G_{ACT})_{i-1}^j} (ER_{DepoACT})_i^j \quad (17)$$

**Table 1.** Summary of Local Historic Management Practices Used in Model Simulations<sup>a</sup>

Time Period	Management	Rotation (year)	Crop	Tillage	Fertilizer
1930–1975	C-C-O-M-M (Diversity)	1	Corn	MP	Manure, Inorganic
		2	Corn	MP	
		3	Oats	–	
		4	Alfalfa	–	
		5	Alfalfa	–	
1976–1990	C-C-B (Intensification)	1	Corn	CP	Broadcast Urea
		2	Corn	CP	
		3	Soybean	CP	
1991–2010	STC-NTB (Conservation)	1	Corn	FC	Anhydrous Ammonium
		2	Soybean	–	

<sup>a</sup>MP, moldboard plow; CP, chisel plow; FC, field cultivator.

where  $(SOC_{NetErodACT})_i^{j-1}$  is the stock of SOC entering CV  $i$  from the upslope; and  $(ER_{DepoACT})_i^j$  is the enrichment ratio of monthly-aggregated material being deposited within CV  $i$  (see equation (14)).

### 2.2.3. Updating SOC Stocks

Using the above outputs from WEPP and the ER module as inputs to the CENTURY model, CENTURY is run sequentially for each CV along the downslope, simulating SOC dynamics from the impact of management and climatic events. Stocks of available SOC within the soil active layer are first determined (equation (1)).

At the end of each month  $j$ , the net change in total SOC in the soil active layer of CV  $i$ ,  $(\Delta SOC_{ACT})_i^j$ , in g C/m<sup>2</sup>, is calculated as follows based on inputs from equations (15) and (17).

For net erosion,

$$(\Delta SOC_{ACT})_i^j = (SOC_{ACT})_i^j - (SOC_{ACT})_i^{j-1} \cong (STAB_{ResD_{ACT}} - R_{HetSOC_{ACT}} - SOC_{NetErodACT})_i^{j-1} \quad (18a)$$

For net deposition,

$$(\Delta SOC_{ACT})_i^j = (SOC_{ACT})_i^j - (SOC_{ACT})_i^{j-1} \cong (STAB_{ResD_{ACT}} - R_{HetSOC_{ACT}} + SOC_{NetDepoACT})_i^{j-1} \quad (18b)$$

where  $STAB_{ResD_{ACT}}$  is the net amount of SOC that was stabilized from decayed residue and root stocks for the month (g C/m<sup>2</sup>; assumption 8; see Appendix A for more detail); and  $R_{HetSOC_{ACT}}$  is the heterotrophic soil respiration during SOC decomposition for the month (g C/m<sup>2</sup>; see Appendix A for more detail).

## 3. Study Site Characteristics

### 3.1. Topographic Characteristics

The representative hillslope selected here is located within a region of the Clear Creek watershed where the predominant soil series is Tama (fine-silty, mixed, superactive, mesic Typic Argiudoll), a mollisol, or prairie-derived soil, that is well drained and formed from loess [Bettis *et al.*, 2003]. Since European settlement, over 80% of the watershed has been converted from intrinsic prairie conditions to row crop agriculture.

Although the watershed features a mosaic of convex and concave hillslopes [Dermisis *et al.*, 2010], the selected representative hillslope has a convex, downslope curvature as it represents the worst-case scenario in terms of soil and SOC loss [e.g., Huang *et al.*, 2002; Rieke-Zapp and Nearing, 2005; Hancock *et al.*, 2010; Dermisis *et al.*, 2010]. The representative hillslope has an elevation drop of 22.5 m along a downslope length of 430 m yielding a declination of 5%, which is the approximate average gradient for the watershed [Dermisis *et al.*, 2010].

For the case study, both upslope and downslope zones (CVs) have the same soil series, which is Tama. The representative hillslope does not extend all the way to the floodplain where the dominant soil series is Colo. The length and average gradient of the upslope were 320 m and 5.8%, respectively, and of the downslope, 110 m and 3.5%, respectively.

### 3.2. Management Practices

A detailed time series of local, historical management practices is provided in Table 1. The first cultivation practices were introduced around 1930 following a final burn and intensive breakup of prairie sod with

the moldboard plow [Hart, 2001]. A 5 year diverse crop rotation of corn-corn-oat-meadow-meadow (CCOMM) with organic fertilizer was then adopted. In years 1 and 2 of that rotation, corn (*Zea mays*) was planted and the moldboard plow was used for both spring and fall tillage. Oats (*Avena sativa*) and alfalfa (*Medicago sativa*) were planted simultaneously in year 3 of the rotation with the oats acting as a companion crop to protect the alfalfa from excessive sunlight exposure and weed competition. Grain harvest of the oats was performed in late summer of year 3 while in years 4 and 5, the alfalfa was cut and baled for hay twice per year. In each year of this 5 year rotation, manure applications were applied in both spring and fall. However, in 1951, these manure applications were replaced with inorganic fertilizers [Keeney and Hatfield, 2008].

During the early 1970s, grain prices and demand began to surge, which prompted shifts of many biodiverse crop rotations (e.g., CCOMM) to more intensified production of other commodity crops [Rupnow and Knox, 1975; Trautmann et al., 1985]. From 1976–1990, soybeans (*Glycine max*) replaced oats and alfalfa grasses in a 3 year rotation of corn-corn-beans, CCB. The CCB management period consisted of larger fertilizer applications and higher tillage intensity with the use of the chisel plow [Reicosky et al., 1995; Keeney and Hatfield, 2008].

In the 1990s, intensified practices were replaced with more conservative tillage practices, including the 2 year corn-soybean rotation of spring till corn/no-till bean, STC-NTB [Abaci and Papanicolaou, 2009]. During corn production in the first year of the rotation, a field cultivator performed reduced spring tillage prior to planting. In the second year of the rotation, soybeans were planted under no-till conditions, with only minor disturbances to the soil from ripple coulters to chop up and remove residue stubble when planting. Fertilizer applications of anhydrous ammonium were knifed into the soil following soybean harvest when soil conditions were favorable [Keeney and Hatfield, 2008].

### 3.3. Climatic Conditions

Due to the midcontinental location of Iowa, the climate for Clear Creek is characterized by hot summers, cold winters, and wet springs [Highland and Dideriksen, 1967]. Daily high temperatures reach an average July maximum of 30 °C, while daily low temperatures reach an average minimum of –10 °C in February [Markstrom et al., 2012]. Average annual precipitation is approximately 876 mm/yr with convective thunderstorms prominent in the early summer and snowfall in the winter [Iowa Environmental Mesonet (IEM), 2015]. For site-specific information, the observed data from a neighboring weather station found in Williamsburg, IA was used [Arnold and Williams, 1989; Gete et al., 1999; Abaci and Papanicolaou, 2009]. We focus on the period of 1930–2010 as this is the period coinciding with the different management periods described earlier (see Table 1).

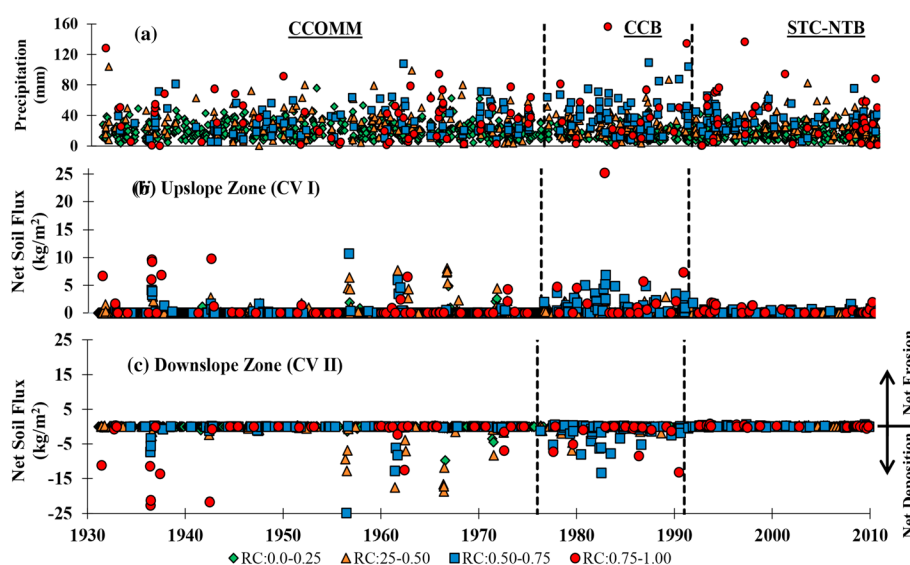
The time series of historic monthly precipitation for the period of 1930–2010 highlights a sequence of seasonal Gaussian distributions, with the peak rainfall in the watershed being received in May and June of each year [Abaci and Papanicolaou, 2009]. In addition to the seasonal variability, several notable extreme climatic events, namely, floods and droughts have occurred throughout this time period, with implications to the overall carbon cycle [Reichstein et al., 2013]. Two major flooding events occurred in years 1982 and 1993 [Heinitz, 1986; Mutel, 2010] and an intensive drought period in 1988 [Handler, 1990].

## 4. Methodological Procedures

### 4.1. Model Initialization and Calibration

Prior to performing model simulations, the initialization and calibration steps of the loosely coupled models were considered carefully. Careful attention was first placed on the initialization of CENTURY to ensure that the initial stocks of SOC adequately represented the conditions found within the active layer (top 20 cm) before introducing cultivation practices. The model was run for an extended period of time prior to 1930 to allow key biogeochemical processes and recalcitrant pools of SOC within CENTURY sufficient time to reach the *pseudoequilibrated state* conditions where conditions do not change in an average sense with time [Metherell et al., 1993]. The year 1930 is considered a benchmark date to our modeling efforts as this is the year that the first cultivation practices were introduced.

Calibration was needed for both models. Topographic data (section 3.1) as well as longitudinal data of changes in management practices (section 3.2) and climate records (section 3.3) helped us perform the calibration procedures. Appendix A provides details of the initialization and calibration steps.



**Figure 4.** Time series of simulated runoff coefficient and soil redistribution. (a) A time series of simulated runoff coefficients (RC) is shown, with corresponding net erosion rates for the (b) upslope and (c) downslope zones of the representative hillslope. The net erosion plots (Figures 4b and 4c) are color coded with the following corresponding RC intervals (0.00–0.25 = green diamond; 0.25–0.50 = orange triangle; 0.50–0.75 = blue square; 0.75–1.00 = red circle). The time series covers the years 1930 to 2010, reflecting CCOMM, CCB, and STC-NTB management practices. Note that the scale of net erosion for the downslope zone is different from the upslope zone due to the presence of net deposition.

## 4.2. Verification

To assess the predictive capabilities of the newly developed framework, samples ( $n = 250$ ) were collected from representative field locations in 2005, 2007, and 2010 and tested for SOC using an elemental analyzer following methods in *Martinotti et al.* [1997] and *Pansu et al.* [2001]. Sampling locations were determined based on results from *Papanicolaou et al.* [2009] and literature found in *Fox and Papanicolaou* [2007, 2008]. Factors hypothesized to induce variation of SOC stocks in the study site (e.g., depth, soil type, management, and gradient) were used to fine tune the sampling locations in both eroding and depositional areas. Comparisons of the measured and the simulated values are presented in section 5.4.

## 5. Analysis of Results

In this section, we present estimates of net erosion/deposition and dry soil bulk density generated from WEPP, as well as ER values generated from the ER module for the upslope and downslope CVs for the period of 1930–2010. These estimates are generated by accounting for rill and interrill contributions and are utilized to generate, via CENTURY, SOC trends where long-term changes in SOC stocks are assessed as a function of historic management practices and climatic conditions for 1930–2010.

### 5.1. Spatial Heterogeneity and Temporal Variability Results of Net Soil Fluxes

Figure 4a provides a time series of the daily precipitation, color coded with simulated daily runoff coefficients (RC) from 1930–2010 to discern the effects of rainsplash from concentrated flow on the magnitude and direction of the soil fluxes. Figures 4b and 4c illustrate the corresponding net erosion and net deposition fluxes for the different management practices.

The RC values throughout the CCOMM management period (1930–1975) averaged 0.18. During the corn production years of the CCOMM rotation (years 1–2), however, RC values were found to be 35% higher than years in grass production (years 3–5 of rotation) despite similar precipitation amounts. During the CCB management period (1976–1990), RCs were highest, averaging 0.30. The highest RC during this time period was during the June flood of 1982 [Heinitz, 1986; Barnes and Eash, 1994], which produced a monthly RC value of 0.65. In the management period of STC-NTB (1991–2010), RC values dropped to an average of 0.26, as conservation tillage methods become prevalent. However, extreme events during the flood of 1993 had an average RC of 0.46, which was almost double the average of the entire period.



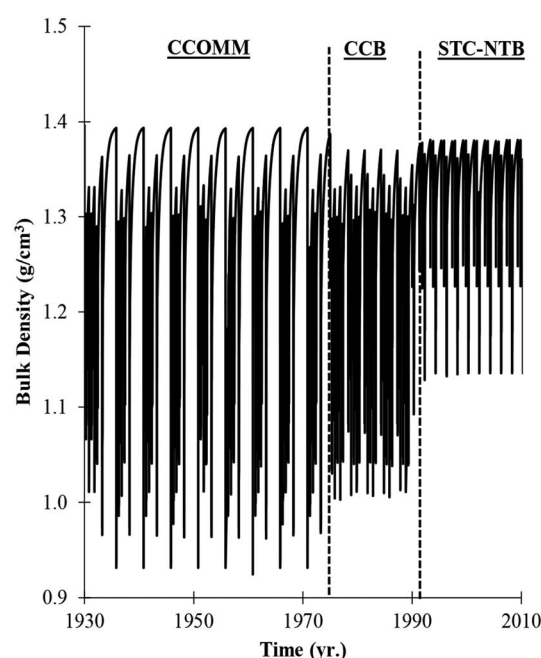
In CV I (Figure 4b), the net erosion events appeared to be more spread out during the CCOMM period comparatively to the CCB and STC-NTB periods. Significant erosion events occurred for the CCOMM period in only two of the 5 years of the rotation when corn was grown and attributed to the decreased land cover from tillage activities. The average net monthly erosion for the entire period was estimated as  $0.48 \text{ kg/m}^2/\text{month}$ . The frequency of erosion events intensified during the CCB period due to reduced land cover in each year of the rotation and increased tillage frequency (3 out of 3 year for CCB versus 2 out of 5 year for CCOMM). The first year of the rotation generally experienced the highest net erosion rates because fall tillage events performed after harvesting soybeans provided less residue cover than corn [Abaci and Papanicolaou, 2009]. The average net monthly erosion during the CCB management period was  $0.99 \text{ kg/m}^2/\text{month}$ , which was more than double the CCOMM rates. The largest net flux for the entire simulation period,  $25.2 \text{ kg/m}^2$ , occurred in the CCB period during the recorded flood event in June of 1982, where 15 cm of rainfall fell on top of an already wet year [Barnes and Eash, 1994]. There was a significant reduction in net erosion rates with the introduction of conservation practices in the STC-NTB period, in the form of reduced tillage and no-till practices [Abaci and Papanicolaou, 2009]. Overall, during STC-NTB management, the soil loss in CV I was found to average  $0.21 \text{ kg/m}^2/\text{month}$ , which was less than half the average rate during the CCOMM management. Similar value ranges for STC-NTB management have been reported in this region (although the emphasis has been in Western Iowa) by Burkart *et al.* [2005] and Karlen *et al.* [2013].

In the downslope control volume, CV II (Figure 4c), the absolute magnitude of net soil fluxes during all management periods was generally less than the magnitude in the upslope CV. During the CCOMM and CCB periods, deposition events in the downslope appeared to “mirror” incoming fluxes from the upslope (Figure 4b), suggesting that contributions from the upslope generally exceeded the transport capacity of flow in the downslope, where the unit flow power term—defined as the amount of flow energy available to mobilize and transport material [Yang, 1973] and expressed in equation (9) through the bed shear stress terms and coefficients as functions of gradient and velocity—was lower comparatively to the upslope. Overall, CV II experienced an average monthly net deposition rate of  $0.66 \text{ kg/m}^2/\text{month}$  in the CCOMM period. Net deposition events continued throughout the CCB management period, with an average net monthly deposition rate of  $1.08 \text{ kg/m}^2/\text{month}$ . This trend was consistent with net fluxes from the upslope during the CCB period being twice as much as the fluxes during the CCOMM period. During the STC-NTB conservation management, net soil fluxes in the downslope switched from net deposition to net erosion, at an average monthly rate of  $0.11 \text{ kg/m}^2/\text{month}$ . The considerably reduced supply of incoming material from the upslope during the STC-NTB period resulted to a supply limited system in CV II and increased mobilization of material derived from the downslope. Hence, although there were still some deposition for certain events, on average, the net flux for each month had generally a positive direction (net erosion). Despite the switch to net erosion, the flux rates in the downslope were less than half the rates in the upslope due to the lower unit stream power (equations (9), (10a), and (10b)). What is worth noting is that despite the positive net flux in both the upslope and downslope CVs for the STC-NTB period, the average monthly flux of material exiting the hillslope for that period was considerably less than the CCOMM and CCB periods due to the effectiveness of the STC-NTB management at reducing net erosion overall.

## 5.2. Bulk Density Spatial and Temporal Variability

As seen in Figure 5, the dry soil bulk density (BD) decreased directly following a tillage event and then increased as cumulative rainfall increased. The simulated BD values ranged between  $0.92$  to  $1.40 \text{ g/cm}^3$ . This is in good agreement with observed BD values of  $0.90$  to  $1.40 \text{ g/cm}^3$ , gathered from a collection of past and current research conducted within the study site [O’neal, 2009; Papanicolaou *et al.*, 2015; <http://critical-zone.org/iml/infrastructure/field-area/clear-creek-watershed>].

The introduction of the moldboard plow spurred interannual fluctuations in BD, decreasing values from  $1.40$  to  $0.92 \text{ g/cm}^3$  during the years in which corn was planted in the CCOMM management period. The BD increased in the months following the tillage events, potentially due to weight consolidation. In rotation years 3–5 when oats or alfalfa was present, the BD increased due to the prolonged absence of tillage events. During the CCB management period, interannual variability in BD decreased ( $1.35$  to  $1.00 \text{ g/cm}^3$ ) as less intensive tillage practices were used in the production of both corn and soybeans, and the BD was unable to reach to the maximum values found in CCOMM because the CCB rotation did not have long-enough “rebounding” periods. In year 1 of the 2 year STC-NTB management practice, fluctuations in BD ranged from



**Figure 5.** Soil bulk density. A time series of simulated daily soil bulk density values for the representative hillslope (black line) as determined by the WEPP model. The time series covers the period from 1930 to 2010 to reflect initiation of tillage. Field measurements of soil bulk density from the study watershed ranged from 0.90 to 1.48 g/cm<sup>3</sup>, which are in good agreement with simulated values [Papanicolaou et al., 2008; O'Neal, 2009].

and net erosion plots in Figure 4 based on the four RC classes. The plots reveal three key findings: (1) there are distinct differences in ER between the upslope and the downslope; (2) ER varies with event magnitude; and (3) management practices affect the ER.

In the upslope CV (Figure 6a), ER values ranged from 0.97 to 3.25 for all runoff-generating storms, with the maximum value reducing systematically from 3.25 to 1.2 from the smallest RC range (0.00–0.25) to the largest RC range (0.75–1.00). The minimum ER value, on the other hand, was similar for all RC ranges, falling between 0.97 and 0.98. Average ER values followed the same trend as the maximum values, also systematically decreasing from 1.27 to 1.00 from the smallest RC range to the largest RC range. The general reduction in ER with increasing RC supports the notion of less preferential mobilization of different size fractions at higher flows where general motion usually occurs [Papanicolaou et al., 2004]. Under these high-flow conditions, the composition of the mobilized soil is similar to the composition of the in situ soil, resulting in little to no SOC enrichment of the transported soil. The results indicated that, on average, mobilized material during CCOMM period was 8% more enriched compared to the in situ soil, whereas material mobilized during the CCB and STC-NTB periods were only 1% more enriched.

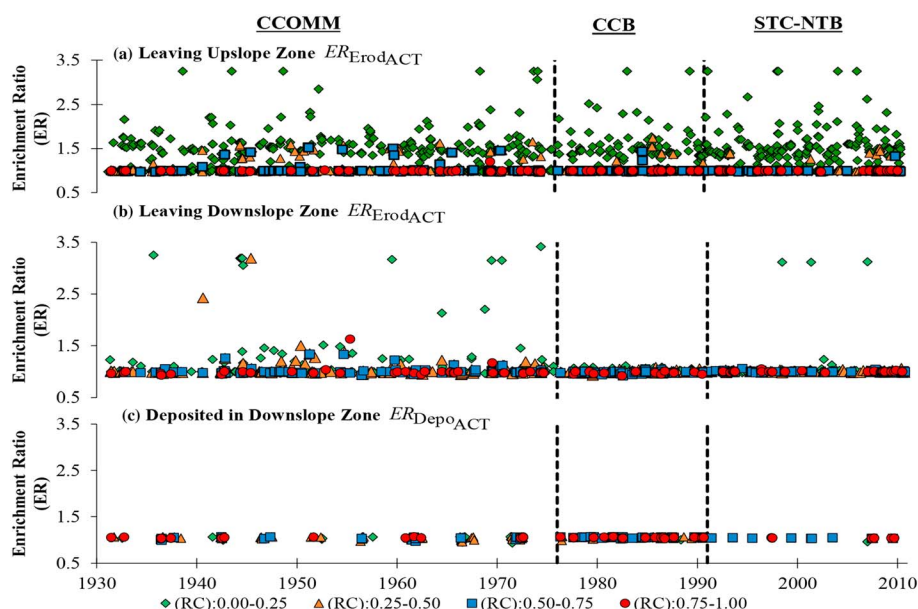
In the downslope CV, the average ER values under net erosion conditions (Figure 6b) were generally lower in magnitude compared to their corresponding values in the upslope CV. Like the upslope, the average ER values in the downslope decreased systematically with increasing RC range from 1.17 to 0.99. The smaller ER values in the downslope compared to the upslope highlighted the importance of rainsplash in the selective transport of finer material on the upper sections of the hillslope [Nadeu et al., 2011; Hu et al., 2013]. On the lower hillslope sections, concentrated flow effects, which tended to mobilize all fractions, were dominant and overshadowed the effects of rainsplash, leading to the smaller ER values. In the downslope CV, the mobilized material during the CCOMM period was only 4% more enriched than the in situ soil, implying that the loss in SOC per unit mass of soil eroded was less in the downslope compared to the upslope (for the same initial SOC content).

1.38 to 1.13 g/cm<sup>3</sup>. The smaller decrease in density was found to be from the reduced spring tillage before corn planting [Abaci and Papanicolaou, 2009]. However, in the second year of the rotation, when no-till was used for soybean production, the even smaller decrease in BD from 1.35 to 1.25 g/cm<sup>3</sup> was due to disturbance of the soil by the planter, which was less intrusive. At the end of the second year, application of the anhydrous also caused the BD to drop to 1.20 g/cm<sup>3</sup>.

Overall, the approximate 20–40% change in BD supports the need to account for temporally updated values of BD in quantifying transport and deposition rates of soil and SOC. Similar trends and the need to account for the chronosequence in BD changes have been reported in the literature [Lal, 2005; Kuhn et al., 2009; Schwärzel et al., 2011; Celik et al., 2012].

### 5.3. Enrichment Ratio Spatial and Temporal Variability

Figure 6 highlights the time series of simulated ER values for the representative hillslope from 1930–2010. Figures 6a and 6b represent material leaving the upslope and downslope CVs, respectively, while Figure 6c represents material being deposited within the downslope CV. In all plots, the ER values are categorized into four classes corresponding to those used for the precipitation



**Figure 6.** Time series of simulated enrichment ratios. A time series of daily simulated enrichment ratios (ER) values of material leaving the (a) upslope and (b) downslope zones of the representative hillslope are provided. (c) The ER values of the material being deposited within the downslope zone, aggregated to the monthly time scale. The ER values are broken into corresponding runoff coefficients (RC), with RC between 0.00 and 0.25 (green diamond); 0.25 and 0.50 (orange triangle); 0.50 and 0.75 (blue square); and 0.75 and 1.00 (red circle).

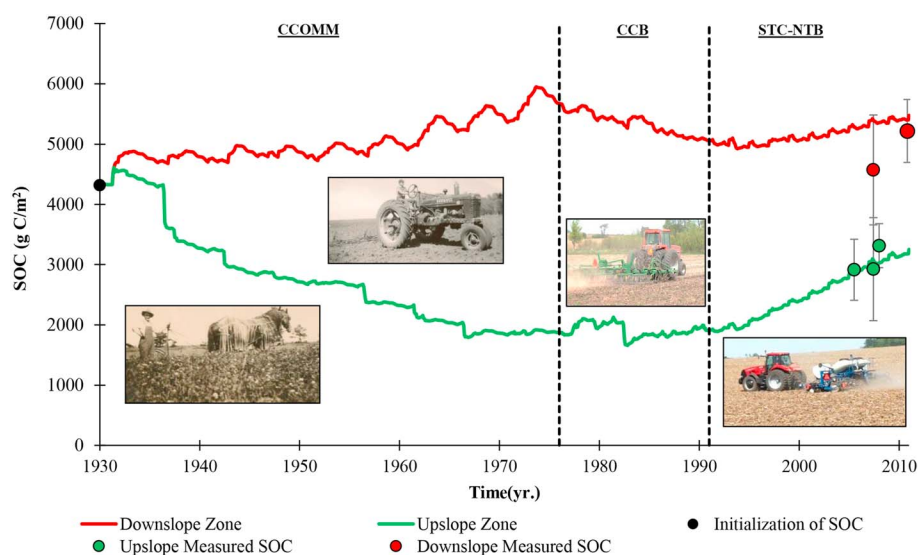
Under net deposition conditions (Figure 6c), material being transported from the upslope CV was deposited onto the active layer of the downslope CV. Deposition processes were also selective, but, on the contrary, favored heavier, generally larger size fractions. The deposited fraction was found to be either less or more enriched compared to the material being transported, depending on the composition of the deposited fractions. This is seen in Figure 6c, where the range of ER values (from equation (14)) falls between 0.93 and 1.07. The depositional patterns in Figure 6c reflect the management practices in each period. There are net deposition events during the two corn production years of the CCOMM period, net deposition events during each year of the CCB period, and net deposition events every other year of the STC-NTB period, reflecting the tillage practices adopted. The ER values for all the management periods suggest that, on average, depositional events resulted in the flux of material that was 3–5% more enriched into the soil. This is consistent with the deposition of larger size fractions containing finer enriched material in their composition [Nadeu *et al.*, 2011].

Overall, the smaller loss in SOC per unit mass of eroded soil in the downslope, combined with the relative enrichment of soil in the active layer, tended to promote higher SOC per unit mass in the downslope relative to the upslope. However, since the ER is concentration ratio, the actual loss or gain in SOC is dependent on the initial stocks of SOC to a large degree [Schiettecatte *et al.*, 2008].

#### 5.4. Effects of Long-Term Changes in LULC on SOC Stocks

Figure 7 provides the time series of simulated monthly SOC stocks within the upslope and downslope CVs of the representative hillslope from 1930 to 2010. The year 1930 was selected to represent the introductory baseline SOC stock value of 4500 g C/m<sup>2</sup> supplied from the initialization (represented by the black dot in Figure 7) right before conversion to agricultural production.

In the upslope CV (green-colored line), the general trend includes (1) significant losses of SOC following conversion to row crop agriculture during the CCOMM period, (2) a “plateaued” recovery period during the CCB management period, and (3) a “rebounding” period during the implementation of current STC-NTB conservation practices. Similar trends have been reported in other assessments of SOC within IMLs [Mann, 1986; Owens *et al.*, 2002; Liu *et al.*, 2003; Tornquist *et al.*, 2009; Brown *et al.*, 2010; Bortolon *et al.*, 2011]. On conversion to row crop production in 1931, there was a sharp, initial spike in SOC stocks due the massive supply of



**Figure 7.** Spatial heterogeneity and temporal variability of SOC. A time series of simulated values of SOC is provided for the upslope (green line) and downslope (red line) zones of the representative hillslope, highlighting the variability of SOC throughout historic management practices from 1930 to 2010. Baseline stocks of SOC acquired during model initialization is plotted (black dot). In addition, field measured values of SOC collected within the upslope (green circle) and downslope (red circle) zones of several hillslopes within the study watershed are compared to corresponding simulated SOC values. Note: Vertical error bars represent the standard deviation of the samples in  $\text{gC/m}^2$ .

organic material delivered to the active layer through tillage-incorporation of prairie grasses. After the spiked flux, there were SOC losses attributed to the combined tillage effects with rainfall-runoff erosion events [Stinner *et al.*, 1983; Tivy, 1990]. This is seen in Figure 7 with a series of “descending staircases” suggesting losses in SOC with time especially throughout the CCOMM period. Residue incorporation rates (i.e., SOC contributions from residue decomposition; see equations (18a), (18b), and (B3)) during the period averaged  $127 \text{ g C/m}^2/\text{yr}$ , while heterotrophic respiration and net erosional SOC losses were 115 and  $67 \text{ g C/m}^2/\text{yr}$ , respectively.

During the CCB management period, enhanced crop production rates from increased fertilizer usage and genetic seed advancements (see Figure C1) began to halt the downward trend of SOC stocks. Residue incorporation rates during this period increased to an average of  $237 \text{ g C/m}^2/\text{yr}$ , while heterotrophic respiration and net erosional losses rose to 131 and  $104 \text{ g C/m}^2/\text{yr}$ , respectively. Overall, SOC stocks kept nearly constant despite a punctuated loss of SOC during the 1982 flood event [Barnes and Eash, 1994].

During the STC-NTB management period, the implementation of conservation practices further decreased erosion rates, while the adoption of high-yield crop hybrids increased plant production such that residue incorporation was greater than the losses due to decomposition and erosion, resulting in SOC stock increases. Here residue inputs averaged  $247 \text{ g C/m}^2/\text{yr}$ , while respiration and erosional losses were 148 and  $29 \text{ g C/m}^2/\text{yr}$ . Loss of SOC due to erosion under STC-NTB was almost 4 times smaller than the previous CCB period. In fact, net erosion fluxes from flooding events in 1993 were “dampened” in part due to the protection offered by increased residue cover from conservation (reduced and no-till) practices [Rhoton *et al.*, 2002]. Toward the end of the simulation, SOC stocks appear to approach a new equilibrium value [Six *et al.*, 2002; Stewart *et al.*, 2007], building at a rate of  $71 \text{ g C/m}^2/\text{yr}$ , which is comparable to increases reported by Reicosky *et al.* [1995].

SOC within the downslope net depositional CV (red colored line) for all periods was found to be much higher than the upslope net erosional CV, which has been reported in the literature [e.g., Stavi and Lal, 2011; Du and Walling, 2011; Navas *et al.*, 2012; Wang *et al.*, 2015]. Throughout the CCOMM period, the gradient of SOC stocks increased as the frequency of deposition events (Figure 4c) and production rates also increased starting in the late 1950s (see Figure C1). Residue incorporation rates during this period averaged  $196 \text{ g C/m}^2/\text{yr}$ , while heterotrophic respiration was  $217 \text{ g C/m}^2/\text{yr}$ . Both of these rates were more than double the values found in

the upslope. In addition, SOC losses due to erosion in the downslope were minimized, averaging around  $4 \text{ g C/m}^2/\text{yr}$ , which is over 10 times less than upslope losses. The average annual stock of SOC deposited from CV I contributions was  $55 \text{ g C/m}^2/\text{yr}$ . This finding could have major implications to the overall carbon budget of the system as most of the mobilized material was not actually exiting the hillslope.

During the CCB period, the downslope experienced a constant degradation in SOC stocks. Residue incorporation and heterotrophic respiration rates averaged 226 and  $305 \text{ g C/m}^2/\text{yr}$ , respectively. The rotational switch from grasses to soybean production not only decreased organic inputs (less biomass) into the soil but also enhanced microbial activity through increased tillage frequency [Stinner *et al.*, 1983; Tivy, 1990]. Average SOC losses due to erosion increased to over twice the CCOMM rates at  $12 \text{ g C/m}^2/\text{yr}$ , while fluxes of deposited SOC from CV I contributions decreased to  $50 \text{ g C/m}^2/\text{yr}$ .

In the STC-NTB management period, the SOC stock began to slowly build and continued to rise, but at a slower rate than the corresponding period for the upslope. Residue inputs averaged  $291 \text{ g C/m}^2/\text{yr}$ , while respiration losses were  $235 \text{ g C/m}^2/\text{yr}$ . Erosional SOC losses in the downslope during this period, however, were the highest of all periods, matching rates in the upslope at  $34 \text{ g C/m}^2/\text{yr}$ . Deposition of SOC during this period was negligible due to the reasons outlined earlier (see section 5.1).

Lastly, Figure 7 also provides a comparison of simulated SOC stocks with field measured values of SOC from a field site in Clear Creek that exhibit nearly identical properties with those selected for the representative hillslope during the simulations (green dot represents values from upslope; red dot represents values from downslope). The figure shows good correspondence between the measured and the simulated values for the representative hillslope. Field values of SOC in the upslope and downslope zones are both increasing over time, with the downslope values higher than the upslope values, which is consistent with the simulation and literature reports [e.g., Liu *et al.*, 2003].

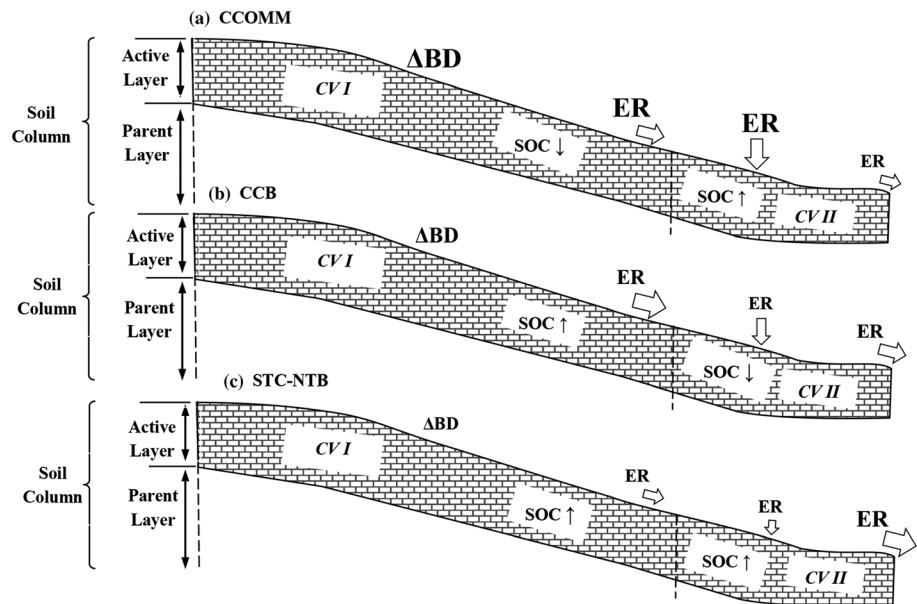
## 6. Discussion and Conclusions

This paper offers an improved methodological framework to account for the collective effects of soil erosion on SOC redistribution in IMLs by spatially simulating the key processes described in Figure 1, taking into consideration monthly-aggregated changes in ER and BD. The framework loosely couples two established process-based models, WEPP and CENTURY, to incorporate the effects of the described landscape features on SOC stocks. A newly developed ER module is used to overcome some important limitations of WEPP by accounting for (1) textural updates of the active layer, (2) the enrichment of material being deposited on the hillslope, and (3) explicitly considering the effects of splash-driven interrill erosion on ER estimates.

The framework is applied in Clear Creek to a representative hillslope that is discretized into two CVs, namely, an upslope net erosional zone and a downslope net depositional zone, to simulate spatial and seasonal changes in SOC stocks due to historical long-term changes in LULC (Table 1). Figure 8 summarizes the simulation results, illustrating the effects of management practice and hillslope location on changes in net soil fluxes, ER, BD, and associated SOC stocks. In the figure, the hollow arrows represent net soil fluxes, where net erosional fluxes are oriented in the downslope direction and net depositional fluxes are oriented vertically downward into the soil active layer. The sizes of the arrows represent the relative magnitudes of the fluxes; larger arrows indicate greater fluxes (and vice versa). SOC symbols with an upward arrow represent gains in SOC stocks while a downward arrow represents loss in SOC stocks. For ER and BD, the sizes of the symbols represent the relative magnitudes of the quantities.

During the CCOMM and CCB management periods, erosion fluxes from the upslope were generally higher than erosion fluxes from the downslope due to a greater supply of material from the upslope to the downslope resulting in a reduced capacity of flow to mobilize material in the downslope. On the contrary, during the STC-NTB period, erosion fluxes from the upslope were lower than the fluxes from the downslope since the supply from the upslope was greatly reduced and the flow in the downslope had a higher capacity to mobilize material. The average deposition rate was largest during the CCB period due to the highest supply of material from the upslope, attributed to the greater tillage frequency and the lower soil cover. The deposition rate was smallest during the STC-NTB period due to the least supply of material from the upslope attributed to the effectiveness of conservation practices.





**Figure 8.** Summary of changes in net soil fluxes, BD, ER, and SOC with management practice and hillslope location. The arrows represent net soil fluxes, with erosional fluxes oriented in the downslope direction and depositional oriented vertically into the soil active layer. SOC,  $\Delta$ BD, and ER symbols represent changes in SOC stocks, soil bulk densities, and enrichment ratios, respectively. The sizes of the arrows and symbols reflect the relative magnitudes of the quantities. For changes in SOC stocks, up arrows indicate gains in SOC while down arrows indicate SOC loss.

There was a clear distinction in simulated ER values between the upslope and the downslope. Net erosion fluxes exiting the upslope were consistently more enriched comparatively to net erosion fluxes from the downslope, suggesting that, under the same initial SOC stocks, SOC losses per unit eroded soil mass in the upslope would be greater than SOC losses per unit eroded soil mass in the downslope. The higher ER values in the upslope were attributed to the relatively more important role of rainsplash (associated with greater selective transport of finer material) on the upper sections of the hillslope comparatively to the lower sections, where concentrated flow effects were more important. Enrichment of eroded material was largest during the CCOMM period due to rainfall-runoff events with low runoff coefficients that preferentially transported finer fractions.

The simulations also highlighted the importance of accounting for the enrichment of the soil active layer in the downslope through the preferential deposition of larger size fractions containing finer enriched material in their composition. On average, deposited material was 3–5% more enriched than the mobilized material from where they deposited. Furthermore, the ER values of material eroded from the downslope were generally close to one as the dominant erosion processes and updated soil textures were such that mobilized material was just as enriched as soil in the active layer. This finding has implications on the fraction of the enriched organic carbon material that gets delivered into the stream under different management practices [Dalzell *et al.*, 2007].

The fluctuations in BD were greatest during the first 2 years of the CCOMM rotation due to the use of the moldboard plow, which was the most intrusive tillage implement. The lowest BD fluctuations were observed during the STC-NTB due to the conservation practices adopted. Overall, the changes in BD during the simulation ranged between 20–40%, supporting the need to account for temporally updated values of BD in quantifying SOC fluxes.

The trends in SOC stocks differed between hillslope locations. In the upslope, SOC stocks declined during the CCOMM period due to intrusive tillage activities and high-erosion rates but increased during the CCB and STC-NTB periods. The increase during the CCB period despite the highest erosion rates was due to enhanced crop production rates from increased fertilizer usage and genetic seed advancements. The continued increase during the STC-NTB period was also due to the lower erosion rates stemming from conservation tillage practices. In the downslope, SOC stocks increased during the CCOMM period due to net deposition



and increased crop production. During the CCB period, however, the stocks decreased despite the high deposition rates due to reduced organic inputs from soybean and increased heterotrophic respiration from increased tillage frequency. SOC stocks increased during the STC-NTB period despite the greater erosion rates from the zone due to reduced heterotrophic respiration rates from conservation tillage and increased crop production rates.

Overall, the simulated SOC trends were in agreement with measured trends and values from a field site in Clear Creek that exhibited nearly identical properties with those of the representative hillslope used for the simulations (Figure 7). The field values of SOC in the upslope and downslope are both increasing over time, with the downslope values higher than the upslope values, which is consistent with the simulation results and literature reports [e.g., *Liu et al.*, 2003; *Wang et al.*, 2015].

As with any framework, there are some caveats associated to the approach considered herein. First, in our analysis we assumed that the soil composition of the active layer in 1930s is similar to the composition of the current active layer. This may not be the case in certain regions of the under investigation watershed where significant soil degradation may have occurred yielding the removal of the A horizon. A recent hydro-pedologic study by *Papanicolaou et al.* [2015] has shown that the steeper areas in Clear Creek with gradients higher than 5% may experience significant degradation resulting in significant coarsening of the top soil.

Second, the framework considers fixed size fractions estimated from empirical relationships developed by *Foster et al.* [1985]. For our site, this produced size fractions with median diameters ranging from 0.002 to 0.48 mm. In reality, however, there may be larger size fractions or aggregates enriched in SOC [*Di Stefano and Ferro*, 2002; *Zheng et al.*, 2012] whose mobilization and deposition could impact SOC dynamics on the hillslope as they offer further protection to the organic matter trapped within their structure [*Berhe et al.*, 2012]. Furthermore, it is assumed that the median diameters of the size fractions do not change under either the impact of rainsplash or hydraulic shear, or as they travel downslope. This may not be the case, as mobilized fractions may break down or grow in size due to mechanical, chemical, or biological processes.

Third, it is assumed that a fixed fraction (20%) of the mobilized SOC is oxidized during transport. However, according to *Lal* [2006], the actual magnitude of oxidation may be dependent on the composition of the organic matter. Uncertainty in the estimate is reflected in the broad range of fractions proposed in the literature [e.g., *Beyer et al.*, 1993; *Lal*, 1995; *Schlesinger*, 1990; *Jacinthe and Lal*, 2001; *Smith et al.*, 2001].

Fourth, the framework also adopts the concept of flow transport capacity which is embedded in WEPP as a means of determining whether or not net erosion or net deposition occurs. Under net erosion, the framework assumes that there is no deposition, whereas under net deposition, it assumes that there is no erosion. However, in nature, erosional and depositional processes occur simultaneously and so the soil active layer continually loses and gains SOC during rainfall-runoff events in both erosional (upslope) and depositional (downslope) zones [*Cao et al.*, 2012]. This effect may be particularly important in the depositional zone, where material flux from the upslope could be deposited onto the active layer even when the transport capacity formula suggests that there should be net erosion.

Fifth, we assume that residue is uniformly distributed across the hillslope and does not simulate the mobilization and downslope transport of residue by runoff. The impact of residue redistribution on the landscape on SOC dynamics between the erosional and depositional zones is thus not accounted for [*Thompson et al.*, 2008]. Lastly, the framework does not account for organo-mineral complexation phenomena, which appear to affect SOC storage differently in erosional and depositional zones [*Berhe et al.*, 2012]. More research is however needed on this front to shed some light on the actual role that complexation plays in the persistence and storage of SOC in the two zones.

Overall, this study, although limited at the hillslope scale, offers some insight of what it will take in terms of human activity and here in terms of conservation practices to reverse further degradation of SOC. To assess the impact of management on SOC budgets at a larger scale where policy needs to be made (e.g., watershed), more detailed representation of the landscape and heterogeneous features present is needed [*Young et al.*, 2014]. High-resolution elevation data, like repeated lidar, could be incorporated into future modeling efforts to identify flow pathways more precisely, as well as track the geomorphic evolution of the landscape stemming from a sequence of erosion or deposition events [*Young et al.*, 2014]. In this case, flow pathways and connectivity of the landscape with neighboring units must be considered. Future research should more

explicitly account for the role of the drainage network on SOC storage as the eloquent work of *Liu et al.* [2011] has shown may play a significant role in SOC stocks as well as the role of exchanges between soil and atmosphere in IMLs.

## Appendix A: Surface/Subsurface Flow Formulation

During a storm event, runoff is routed along the downslope of sequential control volumes (CVs) using the kinematic wave equation:

$$h_{i,j} + q_{i,j} = q_{li} \quad (\text{A1a})$$

where  $i$  denotes space; the CV element  $i$ ;  $j$  denotes time;  $(\cdot)$  denotes first-order derivative;  $h$  is the flow depth (m) within CV  $i$ ;  $q$  is volumetric flow discharge per unit width ( $\text{m}^2/\text{s}$ ) in CV  $i$ ; and  $q_l$  is a source term, a volumetric flow discharge, which incorporates the lateral ( $l$ ) inflow rate of excess rainfall ( $\text{m/s}$ ) to the CV, defined as follows:

$$q_{li} = r_i - f_i \quad (\text{A1b})$$

where  $r$  is the rainfall rate ( $\text{m/s}$ ); and  $f$  is soil infiltration rate ( $\text{m/s}$ ). In equation (A1a), the left-hand side term  $q$ , is estimated using a typical power law, depth-discharge relation:

$$q = \alpha h^{3/2} \quad (\text{A2})$$

where  $\alpha$  is the kinematic depth-discharge coefficient determined as  $\alpha = C\sqrt{S_o}$ ;  $C$  is the Chezy roughness coefficient; and  $S_o$  denotes the spatially average surface gradient of the CV. The infiltration rate of the active layer,  $f$ , in (equation (A1b)), is determined using the modified Green-Ampt equation to account for the effects of management and land use on flow partitioning through the inclusion of the effective hydraulic conductivity term:

$$f_i = F_{i,j} = \left( \frac{\Psi \partial_d + F_i}{F_i} \right) K_{ei} \quad (\text{A3a})$$

where  $\Psi$  is the average capillary potential (m);  $\partial_d$  is the soil moisture deficit (m/m);  $K_e$  is the effective hydraulic conductivity ( $\text{m/s}$ ) that accounts for the collective effects of surface roughness and developed crust, tillage, raindrop impact, as well as canopy and residue cover within CV  $i$  [Kidwell et al., 1997]; and  $F$  is the cumulative infiltration depth (m), which is iteratively determined by applying the Newton-Raphson method to the equation:

$$F = K_e DT + \Psi \partial_d \ln \left( 1 + \frac{F}{\Psi \partial_d} \right) \quad (\text{A3b})$$

where  $DT$  is a time period (s). All terms in equations (B1)–(B3) are written for the CV element  $i$ .

## Appendix B: SOC Decomposition Formulation

In CENTURY, the mass of SOC that is decomposed per unit area during a period  $DT$ ,  $D_{\text{SOC}_{\text{ACT}}}$ , and within the active layer ( $\text{g C/m}^2$ ), or rate of decay, is approximated by a multiparametric equation [Parton et al., 2007] (assumption 3):

$$(D_{\text{SOC}_{\text{ACT}}})_i^j = (\text{SOC}_{\text{ACT}})_i^{j-1} (K_{\text{SOC}_{\text{ACT}}} \text{ANERB}_{\text{ACT}} \text{CDI}_{\text{ACT}} \text{TEX}_{\text{ACT}} \text{TILL}_{\text{ACT}})_i^{j-1} DT \quad (\text{B1})$$

where  $(\text{SOC}_{\text{ACT}})_i^{j-1}$  is the stock of SOC ( $\text{g C/m}$ ) present within the active layer of CV  $i$  at time  $j-1$ ,  $K_{\text{SOC}_{\text{ACT}}}$  is the maximum, equilibrated SOC decomposition rate (one per year);  $\text{ANERB}_{\text{ACT}}$  is a coefficient that adjusts  $K_{\text{SOC}_{\text{ACT}}}$  due to anaerobic conditions and oxygen availability (–), which are dictated by the soil drainage, or downslope saturation;  $\text{CDI}_{\text{ACT}}$  the Climatic Decomposition Index, a correction coefficient that adjusts  $K_{\text{SOC}_{\text{ACT}}}$  for seasonal changes in temperature moisture (–);  $\text{TEX}_{\text{ACT}}$  is a coefficient that accounts for soil texture effects on  $K_{\text{SOC}_{\text{ACT}}}$  (–); and  $\text{TILL}_{\text{ACT}}$  is a multiplier effect for enhanced  $K_{\text{SOC}_{\text{ACT}}}$  following tillage under different management practices (–).

In a similar manner, the decomposition of residue,  $D_{\text{Res}_{\text{ACT}}}$ , within the active layer ( $\text{g C/m}^2$ ) is expressed as follows:

$$(D_{\text{Res}_{\text{ACT}}})_i^j = (L_{\text{ACT}})_i^{j-1} (K_{\text{Res}_{\text{ACT}}} \text{ANERB}_{\text{ACT}} \text{CDI}_{\text{ACT}} \text{TILL}_{\text{ACT}})_i^{j-1} DT \quad (\text{B2})$$

where  $L_{ACT}$  is the stock of soil residue within the active layer ( $\text{g C/m}^2$ ); and  $K_{ResACT}$  is the maximum, equilibrated residue decomposition rate (one per year).

A portion of the decayed stocks in equations (B1) and (B2) can be stabilized into more decay-resistant forms of SOC within the soil active layer based on soil texture, prevalent C/N ratio, and residue lignin content [Sorensen, 1981; Van Veen *et al.*, 1984; Holland and Coleman, 1987]. The portion transferred to the more decay-resistant pools is what we define herein as “stabilized SOC” with the recognition though that this term has been presented in the literature in different ways somewhat inconsistent [Berhe and Kleber, 2013]. Taking into account these factors, the amount of SOC stabilized,  $STAB_{SOCACT}$ , in the active layer ( $\text{g C/m}^2$ ) is expressed as follows (assumption 8):

$$(STAB_{SOCACT})_i^j = STAB_{SOCDACT} + STAB_{ResDACT} = f_{SOC}(D_{SOCACT})_i^j + f_{Res}(D_{ResACT})_i^j \quad (B3)$$

where  $f_{SOC}$  is the fraction of decomposed SOC that is stabilized (values found in Parton *et al.* [1987]); and  $f_{Res}$  is the fraction of decomposed residue that is stabilized as SOC based on lignin availability [Melillo *et al.*, 1982]. Lastly, the portion of decayed stocks that is not stabilized within the soil is lost from the active layer in the form of  $\text{CO}_2$ , defined here as heterotrophic soil respiration ( $\text{g C/m}^2$ ),  $R_{HetACT}$ , and expressed as follows:

$$(R_{HetACT})_i^j = R_{HetSOCACT} + R_{HetResACT} = (1 - f_{SOC})(D_{SOCACT})_i^j + (1 - f_{Res})(D_{ResACT})_i^j \quad (B4)$$

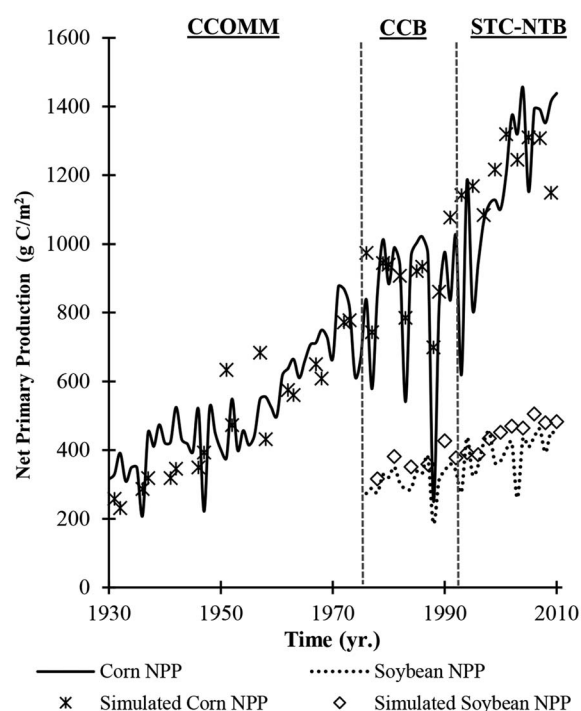
## Appendix C: Initialization and Calibration Steps

During the initialization period, intrinsic prairie conditions were considered, as a tall grass has been historically found throughout much of Iowa and the Midwest with minor grazing from free-range buffalo, and a 10 year fire frequency (Table C1) [Hart, 2001; Weaver, 1968; Delucia *et al.*, 1992; Macha and Cihacek, 2009; Kaiser, 2011]. For the representative hillslope, an initial stock of SOC (at  $t=0$ ) was first estimated as  $5500 \text{ g C/m}^2$  using the semiempirical relation developed by Burke *et al.* [1989], which considers average annual climatic and soil texture conditions as input parameters (see Table C1). Then, assuming the presence of the Big Bluestem (*Andropogon gerardii* Vitman), the model was run until the SOC stocks reached pseudoequilibrated values of  $4520 \text{ g C/m}^2$  after approximately 4000 years. This pseudoequilibrated value of SOC agrees with the ranges of the reported field measured SOC stocks found within the Dinesen prairie, a remnant, native tallgrass prairie, the closest “undisturbed” location with SOC measurements to the study site [Harden *et al.*, 1999; Manies *et al.*, 2001]. No initialization of WEPP was needed since it was reasonable to assume that SOC mobilization due to erosion during the prairie period was insignificant other than some episodic events.

Typically, the calibration procedure for WEPP starts with flow (i.e., the driving mechanism for upland erosion) and continues with the sediment component [Santhi *et al.*, 2001]. Additional information is needed in the model for key state variables such as the effective hydraulic conductivity, critical erosional strength, and residue cover, which is available for the study site [see Abaci and Papanicolaou, 2009, Tables 12 and 13]. Because

**Table C1.** Input Data for Model Initialization

Input Data	Units	Range	Reference
<i>Soil Properties</i>			
Sand content	%	5.0–15.0	Current study
Silt content	%	60.0–70.0	Current study
Clay content	%	18.0–30.0	Current study
<i>Climate</i>			
Monthly precipitation	(cm/month)	6.47–8.14	Abaci and Papanicolaou [2009]
Monthly temperature	(°C)	8.83–10.83	IEM [2015]
<i>Management-Prairie-Big Bluestem</i>			
Lignin content		0.17	Saxena and Stotzky [2001]
Grazing frequency	(months/year)	2	Hart [2001]
Grazing intensity	% vegetation consumed	30	Hart [2001]
Fire frequency	# years without fire	10	Collins and Wallace [1990]
Fire intensity	% vegetation consumed	90	Collins and Wallace [1990]



**Figure C1.** Model calibration. Local corn and soybean grain yield data and field measured values of vegetative carbon content as well as harvest indices were used to generate a times series of estimated aboveground net primary production (NPP) values of corn (solid black line) and soybeans (dashed black line) from 1930 to 2010 as well as simulated values of corn NPP (black cross) and soybean NPP (black diamond). The simulated values of NPP are the average of the upslope and downslope zones.

1993; Prince *et al.*, 2001], the grain mass was used to estimate aboveground biomass. The aboveground biomass and grain mass data were then converted to a carbon density, namely, NPP, by utilizing vegetative carbon contents of corn and soybean plants (i.e., leaves, stems, and grain) collected within the study site (A. N. Papanicolaou, unpublished data, 2014). Measured values of corn and soybean plant carbon contents were found to be in good agreement (correlation above 90%) with reported literature values [Latshaw and Miller, 1924; Machinet *et al.*, 2009].

A sensitivity analysis revealed that precipitation and temperature data were sensitive parameters within the CENTURY plant production submodel [Xiao *et al.*, 2004; Schurgers *et al.*, 2011]. For this reason, local climate data from the Williamsburg site was used to simulate the time series of NPP from 1930–2010. The simulation period was partitioned into the following key crop rotations: CCOMM from 1930 to 1975; CCB 1976 to 1990; and STC-NTB 1991 to 2010 (see Table 1), with soybeans present in years 1976–2010, and corn present throughout the entire simulation. During the calibration efforts the reported statewide nitrogen fertilizer application rates for Iowa were adopted [NASS, 2012].

Comparisons of NPP values estimated using the above mentioned methods and simulated NPP from 1930 to 2010 are shown in Figure C1. In terms of corn, there is an overall upward trend in simulated NPP from 1930 to 2010 which agrees well with the estimated NPP values. During this time period, NPP increases from 350 g C/m<sup>2</sup> to around 1400 g C/m<sup>2</sup>. Large variability in NPP occurs during CCB management, between the years 1980 to 1993, due to reported extreme climatic events, namely droughts and flooding [Rosenzweig *et al.*, 2002].

For soybeans (1976–2010), simulated values increase from 288 g C/m<sup>2</sup> to around 450 g C/m<sup>2</sup>. Overall, the simulated and estimated NPP appear to be in an agreement ( $R^2$  value = 0.84) for the entire period from 1930 to 2010.

the procedural steps for calibrating WEPP have been extensively described in the literature [e.g., Flanagan *et al.*, 2007; Papanicolaou and Abaci, 2008; Abaci and Papanicolaou, 2009; Dermisis *et al.*, 2010] an emphasis here has been placed on the calibration for CENTURY.

The plant production submodel of CENTURY was calibrated to ensure accurate inputs of plant material into the soil active layer. Based on prior studies, the CENTURY model must be first calibrated using reported ranges of aboveground net primary production (NPP) in this region, defined here as the total net carbon stored in aboveground vegetation (i.e., stems, leaves, and grain) [e.g., Chapin *et al.*, 2002]. Having the NPP estimated values within the measured ranges was deemed important for ensuring that CENTURY incorporates the correct inputs of aboveground C allocation for simulating belowground C allocations and stocks. The first step of the calibration process involved the collection of historic corn and soybean grain yield data (1930–2010) from Iowa County, where is the study location [National Agricultural Statistics Service (NASS), 2012]. Yield data were converted to total grain mass and corrected for seed moisture, which is commonly assumed to be 15.5% [Lauer, 2002]. Using unique harvest indices, defined here as the ratio of grain to total plant mass [Huehn,

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